

GAMMA-RAY BURSTS MAY BE BIASED TRACERS OF STAR FORMATION

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ABSTRACT

Based on a simulation of galaxy formation in the standard cosmological model, we suggest that a consistent picture for Gamma-Ray Bursts and star formation may be found that is in broad agreement with observations: *GRBs preferentially form in low metallicity environments and in galaxies substantially less luminous than L_** . We find that the computed formation rate of stars with metallicity less than $0.1 Z_\odot$ agrees remarkably well with the rate evolution of Gamma-Ray Bursts observed by Swift from $z = 0$ to $z = 4$, whereas the evolution of total star formation rate is weaker by a factor of about 4. Given this finding, we caution that any inference of star formation rate based on observed GRB rate may require a more involved exercise than a simple proportionality.

Subject headings: stars: abundances — supernovae: general — galaxies: formation — cosmology: theory

1. INTRODUCTION

The intriguing observational linkage between long duration Gamma-Ray Bursts (GRBs) and core-collapse supernovae (e.g., Stanek et al. 2003; Hjorth et al. 2003) suggests that the progenitors of GRBs may be very massive stars. This possible connection was predated by a proposed unified picture (Cen 1998). As such, it has been hoped that GRBs may be a good tracer of cosmic star formation (Wijers et al. 1998; Totani 1999; Lamb & Reichart 2000; Blain & Natarajan 2000; Porciani & Madau 2001; Daigne et al. 2006; Coward 2006; Le & Dermer 2007; Li 2007). However, recent observations indicate that typical GRBs may prefer relatively low metallicity environments ($\sim 0.1 Z_\odot$) (Fynbo et al. 2003; Le Floch et al. 2003; Christensen et al. 2004; Fruchter et al. 2006; Stanek et al. 2006) and host galaxies significantly less luminous than L_* (Fruchter et al. 1999, 2006), although there is evidence that the actual spread in metallicity may be wide (Berger et al. 2006; Prochaska 2006; Wolf & Podsiadlowski 2007).

The aim of this *Letter* is to first address the issue of consistency of GRB environment with respect to metallicity and galaxy luminosity, i.e., the galaxy luminosity-metallicity relation, in the context of detailed simulation of galaxy formation in the standard cosmological model. Then, we make predictions on the evolution of GRB rate with redshift and highlight a possible dramatic difference between overall star formation history and GRB rate history, if GRBs are not an unbiased tracer of star formation. In particular, if GRBs are predominantly produced by stars with metallicity $\leq 0.1 Z_\odot$, the GRB rate is expected in our model to rise obstinately from $z = 0$ to $z \sim 5$ by a factor of ~ 100 , when it flattens out towards higher redshift, whereas the overall star formation rate rises rapidly only from $z = 0$ to $z \sim 3$ and is roughly flat from $z \geq 3$ until $z \sim 7$. The evolution of GRB rate with redshift is thus expected to be stronger than that of star formation.

2. EVOLUTION OF GRB AND STAR FORMATION RATES

Observations seem to indicate that GRB galaxy hosts are preferentially dwarf galaxies of about $0.1 L_*$ at low redshift (Fruchter et al. 1999, 2006). This would be surprising, if GRB rate is directly proportional to total star formation rate, because the latter is known to peak in significantly larger galaxies (see, for example, Figure 1 below). The implication is that GRB rate is not exactly proportional to the overall star formation rate. On the other hand, analysis of the metallicity of GRB progenitors suggests that GRB progenitors tend to have relatively lower metallicity of $\sim 0.1 Z_\odot$ than that of typical forming stars at low redshift (Fynbo et al. 2003; Le Floch et al. 2003; Christensen et al. 2004; Fruchter et al. 2006; Stanek et al. 2006). We would like to ask the following question: are these two observational facts consistent in the galaxy formation model in the standard cosmological model?

Figure 1 shows the distribution of SDSS U-band light as a function of the stellar mass of galaxies, with the galaxies being divided into two subgroups according to the mean metallicity of galaxies. The results are based on a cold dark matter cosmological simulation with galaxy formation in a cold dark matter universe (Nagamine et al. 2006; Cen & Ostriker 2006; Cen & Fang 2006) with the following essential parameters: $\Omega_M = 0.31$, $\Omega_b = 0.048$, $\Omega_\Lambda = 0.69$, $\sigma_8 = 0.89$, $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1} = 69 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $n_s = 0.97$. The simulation box size is $85 h^{-1} \text{ Mpc}$ comoving with a number of cells of 1024^3 , giving a cell size of $83 h^{-1} \text{ kpc}$ comoving and dark matter particle mass equal to $3.9 \times 10^8 h^{-1} \text{ M}_\odot$. Given a lower bound of the temperature for almost all the gas in the simulation of $T \sim 10^4 \text{ K}$, the Jeans mass is $\sim 10^{10} \text{ M}_\odot$ for mean-density gas, which is comfortably larger than our mass resolution. Galaxies are produced using a grouping scheme HOP (Eisenstein & Hut 1998) (see Nagamine et al. 2001 for details), which gives a catalog of galaxies each with stellar mass, mean stellar metallicity, luminosities in all SDSS bands, etc.

We see a general trend in Figure 1 that larger galaxies tend to have higher metallicity, albeit a significant dispersion exists (not shown here). Specifically, it is seen that,

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if the stellar metallicity is, say, typically lower than $0.1 Z_{\odot}$ for GRBs progenitors, galaxies of stellar mass $10^{10} M_{\odot}$ is expected to make the dominant contribution, whereas the overall star formation rate is peaked in galaxies of stellar mass $10^{11} - 10^{12} M_{\odot}$. Apparently, this is in broad agreement with observations of GRB being concentrated in dwarf galaxies of metallicity $< 0.1 Z_{\odot}$. This is reassuring in that our simulation that has been shown to produce consistent results compared to the real universe in many other aspects appears to be in broad agreement with observations with regard to the general luminosity-metallicity trend (e.g., Kobulnicky & Kewley 2004) and with the observed preference of GRB hosts of typical metallicity $\sim 0.1 Z_{\odot}$ and typical luminosity $\leq 0.1 L_{*}$.

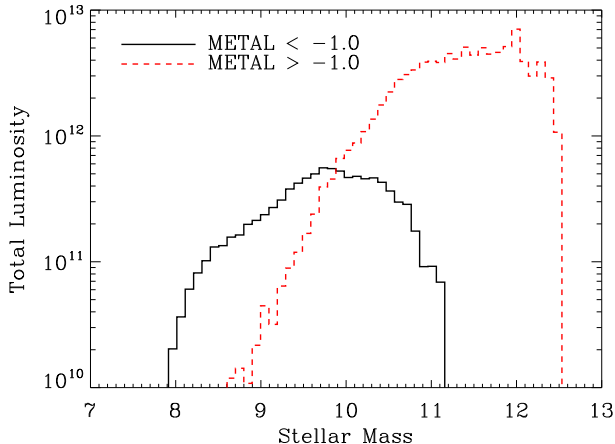


FIG. 1.— shows the distribution of U band light as a function of the stellar mass of galaxies, for two groups of galaxies, one with metallicity greater than 10% of solar metallicity (dashed histogram) and the other with metallicity lower than 10% of solar metallicity (solid histogram).

Having verified that our simulation is able to reproduce the general luminosity-metallicity relation for galaxies, we will take a step further to infer the rate evolution for GRBs, given the computed star formation rate and stellar metallicity as a function of redshift. Since our simulated galaxies are composed of thousands to millions of “stellar” particles, which typically resemble globular clusters, we will use the “resolved” metallicity of individual “stellar” particles. Usually, there is a wide dispersion in stellar metallicity among the “stellar” particles within an individual galaxy, reflecting complicated star formation history of each galaxy.

Figure 2 shows histories of three rates: total star formation (dotted curve), star formation with metallicity less than $0.3 Z_{\odot}$ (dashed curve) and less than $0.1 Z_{\odot}$ (solid curve), respectively. We see that, if GRBs are preferentially hosted by stellar progenitors with metallicity lower than $0.1 Z_{\odot}$, one should expect to see their rate to rise approximately exponentially as a function of redshift from $z = 0$ until $z \sim 5$. This is contrasted with a flattening of the overall star formation rate at a much lower redshift $z \sim 2$ accompanied by only a modest rise (a factor of 2) from $z \sim 2$ to $z \sim 5$.

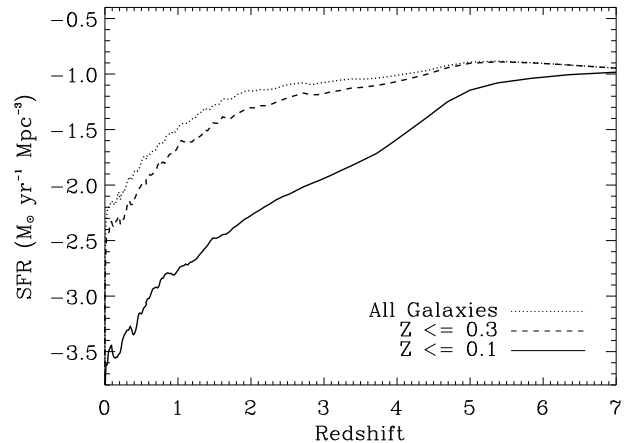


FIG. 2.— shows histories of three rates: total star formation (dotted curve), star formation with metallicity less than $0.3 Z_{\odot}$ (dashed curve) and less than $0.1 Z_{\odot}$ (solid curve), respectively.

We note that, while the overall star formation seen in Figure 2 is higher by a factor of ~ 30 at $z = 4$ than at $z = 0$, the ratio of GRB rate at $z = 4$ to that at $z = 0$ is ~ 120 , if GRB progenitors predominantly have metallicity less than $0.1 Z_{\odot}$, roughly a factor of four larger. This result is, curiously, in remarkable agreement with recent observations of Kistler et al. (2007) where they suggest that the GRBs observed by Swift has an enhanced evolution by a factor of ~ 4 from $z = 0$ to $z = 4$ compared to the overall star formation rate.

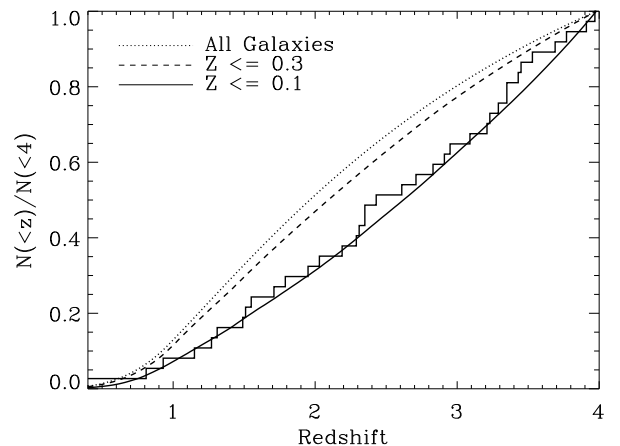


FIG. 3.— shows the cumulative distribution of the observed (steps) and predicted (lines) GRB rates, normalized to the total number of bursts between $z=0$ and $z=4$. See Fig. 2 for line styles. Data shows the distribution of the 36 Swift GRBs taken from Butler et al. (2007). The star formation rate of all-galaxy sample was normalized to the analytic values of Hopkins & Beacom (2006), and the star formation rates for the other two samples was normalized by the same factor.

In the spirit of making as a direct comparison as possible with observations, we shows the cumulative distribution of the observed (steps) and predicted (curves) GRB rates, normalized to the total number of bursts between

$z = 0$ and $z = 4$ in Figure 3, following Kistler et al. (2007). Here, in order to make a direct comparison with Kistler et al. (2007) and to remove uncertainties in the overall star formation rate in our simulation, we normalize the star formation rate of the all-galaxy sample in our simulation to the analytic values of Hopkins & Beacom (2006), as did Kistler et al. (2007). Then, the star formation rates for the other two (lower metallicity) samples are adjusted multiplicatively by the same factor. It is seen that, if one simply assumes that the total GRB rate is proportional to the star formation rate of metallicity less than $0.1 Z_{\odot}$, the observed evolution of GRB rate from $z = 0$ to $z = 4$ is reproduced to a high degree, clearly visible in the good agreement between the solid curve and the step curve in Figure 3.

3. DISCUSSION

Taken all the observational facts together along with our theoretical results, a broadly consistent picture appears to emerge: *GRBs preferentially form in low metallicity environments and (because of the luminosity-metallicity relation) in galaxies substantially less luminous than L_* , and GRB rate evolves more strongly than the overall star formation rate.* Evidently, the observed evolution of GRB rate from $z = 0$ to $z = 4$ can be explained, *if GRBs are primarily produced by massive stars with metallicity less than $0.1 Z_{\odot}$.* Including higher metallicity stars would produce GRB rate evolution from $z = 0$ to $z = 4$ that is inconsistent with observations. Nevertheless, this overall picture would also be consistent with a theoretical preference or possibly requirement of low metallicity for GRB progenitors in the context of “collapsar” models (MacFayden & Woosley 1999; Woosley & Heger 2006).

What is implicitly assumed is that the stellar initial mass function (IMF) has remained the same over the redshift range considered. In other words, whatever metallicity dependence of GRB rate may have, this dependence is assumed not to evolve with redshift. One should note that it is not fully known observationally or understood theoretically how the IMF evolves with time. Therefore, additional possible evolutionary effect of IMF would add another layer of complexity to this issue. It is often thought that lower metallicity environment might favor formation of more massive stars. If GRB progenitors are massive stars, this would then translate to the expectation that additional effect due to an evolving IMF may further steepen

the evolution of the GRB rate with redshift. This, however, is not required or borne out in our analysis. Our results thus imply that the evolution of IMF from $z = 4$ to $z = 0$, if any, appears to be weak.

If we place this result in a larger context of star formation over the entire cosmic history, one might come to the conclusion that, while there may be a dramatic transition of IMF from Population III metal-free stars (Nakamura & Umemura, M. 2002; Abel, Bryan & Norman 2002; Bromm, Coppi, & Larson 2002) to Population II stars at some high redshift (e.g., Cen 2003; Trac & Cen 2007), further evolution of IMF at lower redshift may be modest, in the sense that the mass fraction of high mass stars that are presumably GRB progenitors of the total stellar mass remains relatively constant.

4. CONCLUSIONS

We utilize a simulation of galaxy formation in the standard cosmological model that has been shown to produce results consistent with extant observations of galaxy formation (e.g., Nagamine et al. 2006) to shed light on the relation between GRB rate and star formation rate. We find that a consistent picture for Gamma-Ray Bursts and star formation that is in broad agreement with observations would emerge, *if GRBs preferentially form in low metallicity environments and in galaxies substantially less luminous than L_* .* Because of the increase of metallicity with cosmic time, GRB rate consequently evolves more strongly with redshift than the overall star formation rate. We find that the observed evolution of GRB rate from $z = 0$ to $z = 4$ can be explained, *if GRBs are primarily produced by massive stars with metallicity less than $0.1 Z_{\odot}$,* whereas an inclusion of stars with metallicity as high as $0.3 Z_{\odot}$ yields GRB rate evolution from $z = 0$ to $z = 4$ inconsistent with observations.

Therefore, we reach the conclusion that GRBs may not be a good tracer of cosmic star formation, especially over a long timeline. As a result, a simple inference of star formation rate or its derived quantities such as the ionizing photon production rate at high redshifts, based on the observed GRB rate, should be done with caution and may require careful calibrations.

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